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Chapter 4

Local Effects Arrays

4.1 INTRODUCTION

It is not possible to give a precise definition of "local effects" as considered herein in contrast to "wave propagation effects" dealt with elsewhere in this report. By one possible definition, local effects might be those which affect the components of ground motion with a frequency greater than about 1 Hz (or, alternatively, wavelengths less than 1000 m). Seismologists have tended to concentrate their attention on frequencies less than 1 Hz and there is known to be a large degree of coherence in such frequency components over local areas. In the present context, local effects refer to geologic and topographic anomalies and the manner in which they affect ground motion in the frequency ranges of concern to engineers.

In the most common specification of design ground motions for a building, no consideration is given to possible variations in ground motion over the site occupied by the building. This suffices for many practical purposes. In effect, one uses a single point specification, without consideration of gradients in the motions. However, for some special large structures (such as nuclear power plants, which may experience rocking and twisting input) and for extended structures (such as bridges, dams and pipelines), it is necessary to consider differential motions between points of the earth, that is, to consider horizontal gradients in the motions. The vertical gradient can also be important for embedded structures. In addition, there are other important engineering problems for which knowledge is incomplete, including interaction between soil and structure, soil failure and the nature of very long period motions.

Single Point Specifications

There are several major needs in the area of the single point specification of strong ground motion. These include:

- 1) The recording of ground motions from earthquakes with magnitudes of 7.0 or greater, and the recording of ground motions within a few kilometers of earthquakes with magnitudes of 5.5 or greater. The former type of data is almost completely lacking at this time, while there is little of the latter.

- 2) The clarification of the effects of local soil conditions. There still are major arguments as to when soils amplify or deamplify ground motions and as to the validity of theories for predicting this effect. Other arguments concern just how motions vary near the edges of valleys and across them. The need for data in the near field of major earthquakes is especially strong.
- 3) The gathering of data concerning long period ground motions for engineering applications. At present there are no good data banks of such information.

Gradients in Ground Motion

Here again, several different categories of need exist. These may be grouped as follows:

- 1) Assessment of the validity of theories for the propagation of waves across a site. Theories have been proposed which hypothesize that ground motions sweep across sites as Love waves or Rayleigh waves. These theories imply that significant twisting or rocking motions may be introduced at the base of structures. There is at present little or no data which can be used to assess the validity of these theories.
- 2) Understanding the variation of ground motion with depth. This knowledge is important in defining the input to embedded structures. There are, especially in Japan, a number of instrument arrays aimed at providing this type of data. Additional such arrays are desirable, in order to increase the chances of obtaining data during very strong shaking ($a > 0.2g$).
- 3) Understanding the relative motion of points from 10 m to 1000 m apart in soil. Damage to extended facilities, such as bridges and pipelines, is related largely to such relative motion. Bending strains and especially axial strains are important in the design of buried pipes. Bridge piers may be significantly influenced by local rotational acceleration (rocking or twisting) of the supporting soil. Very little data of this type are available.

Soil-Structure Interaction

This phenomenon comprises two aspects: 1) the compliance of the soil beneath a structure rocking or translating relative to the supporting soil, and 2) the smoothing out of free-field motion by a rigid foundation. These parts are called inertial and kinematic interaction, respectively. Theories are available for both interaction effects, but there is a need to test these theories, particularly those for kinematic interaction.

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Failure of Soil Masses

The following types of ground failure are associated with earthquake motions:

- 1) Liquefaction of deposits of saturated sandy soils
- 2) Settlement and compaction of deposits of dry or partially saturated sandy soils
- 3) Failures of natural slopes and embankments
- 4) Ruptures caused by active surface faults.

Arrays designed to study source mechanism effects will provide considerable insight concerning item 4). Measurement of ground motions within a soil slope as it begins to fail does not seem a profitable area for field investigation. Hence, only the first two items, which are very closely related, will be considered in the design of local effects arrays. While theories for predicting the relationship between ground motion and pore-pressure buildup exist and are widely used, they are quite controversial and there is an almost total lack of applicable data from actual earthquakes.

4.2 RECOMMENDATIONS FOR THE STUDY OF LOCAL EFFECTS

In light of the needs outlined above, the following recommendations are made:

- 1) In the vicinity of each of the sites identified in this volume - and especially in the vicinity of the six high priority sites - from 10 to 20 conventional, off-the-shelf accelerographs should be installed immediately. Later sections of this Chapter indicate how these instruments might be deployed within such regions. The number of installations may be reduced in regions where instruments already exist.
- 2) Within any permanent source mechanism array of the type recommended in this volume, from 10 to 30 additional instruments should be incorporated to:
 - a) record the attenuation of ground motion to distances of 50 to 150 km from the fault
 - b) provide data concerning the effects of local soil conditions, the variation of ground motions across valleys, relative horizontal motions between nearby points and the buildup of pore pressures within saturated sands.

Detailed guidance and recommendations concerning the siting of these instruments are given in later sections of this Chapter.

- 3) A minimum of three, and preferably six, Local Laboratory Arrays should be installed at highly seismic locations throughout the world. These are complex and sophisticated arrays with 25 to 40 instruments. They may include strain gauges and rotational accelerometers. Instruments are deployed both at the surface and down to depths of 50 m to 100 m within an area of 1 km² or less. These arrays would be designed so as to provide detailed data concerning the manner in which ground motions propagate through sites, thereby permitting the validation of theories intended to predict local effects. These Local Laboratory Arrays are discussed in detail in a later section of this Chapter which outlines the special site conditions which are required. These arrays may be incorporated within the permanent source mechanism arrays discussed elsewhere in this volume.
- 4) From 10 to 20 instruments for the study of local effects should be incorporated into the plans for any Mobile Array Laboratory, for the purpose of recording variations of motion across valleys and along other baselines of about 1 km in length. These instruments would be operated in arrays of four to ten devices, to supplement information obtained by fixed local effects arrays.

4.3 TYPES OF LOCAL EFFECTS ARRAYS

A comprehensive program for the study of local effects should involve several different types of arrays, as indicated in Table 4.1. In general, there should be three levels of ground motion arrays, involving different degrees of complexity and sophistication and aimed at different objectives. In addition, there is a need for special arrays involving measurement of ground motion but aimed primarily at providing data and/or testing theories regarding specific engineering problems. Various general features of the proposed types of ground motion arrays are summarized in Table 4.2.

It is quite important that international efforts to install large scale source mechanism, wave propagation and local effects arrays not discourage national efforts to deploy simple extended arrays or coordinated systems of elemental arrays and individual instruments. These national efforts can provide valuable data while the world awaits completion of the more extensive arrays and the first data from these installations. Indeed, it is hoped that the international array program will provide technical assistance in the planning of national efforts in less developed countries and cooperation in the processing and analysis of results from national arrays. In particular, it is important that the international array program encourage and assist the immediate installation of proven strong-motion accelerographs in the vicinity of each of the high priority sites identified in this volume.

TABLE 4.1

TYPES OF LOCAL EFFECTS ARRAYS

Ground Motion Arrays

- A. Local Laboratory Arrays
- B. Simple Extended Arrays
- C. Elemental Arrays

Special Arrays

- A. Soil-Structure Interaction Arrays
- B. Liquefaction Arrays

Local Laboratory Arrays

These are the most complex and sophisticated local effects arrays. They are intended to: 1) provide data concerning relative motions between points in the free field, 2) indicate the nature of wave propagation through a site, and 3) permit testing of theories for computing the propagation of waves through a site. The objective of these arrays is of both scientific and engineering interest. Such arrays form laboratories for studying the nature of near surface ground motions in detail, and may become field laboratories for the evaluation of instruments and the testing of theories concerning soil-structure interaction.

The desired characteristics of Local Laboratory Arrays are discussed in detail in Section 4.4. They are conceived as extending over horizontal distances of the order of 500 m and to depths up to about 100 m. There will be 25 to 40 instruments in each array, including instruments for recording rotation and relative motion directly as well as the more common instruments for recording linear motion at a point. Common time bases and simultaneous triggering are required. Processing of data will require sophisticated methods involving cross-correlations among records. These arrays will be located at sites with specially selected soil conditions. Inherently they are fixed (non-portable) arrays.

A primary siting requirement is that Local Laboratory Arrays receive frequent (about one/year total from all arrays) shakings of 0.05g or greater. Much of scientific and engineering value can be learned from this intensity, and the instrumentation must have adequate resolution at this level of shaking. On the other hand, the instrumentation also must record any very strong motions which might occur.

A Local Laboratory Array may exist independent of arrays that might be installed for purposes of studying source mechanisms although enough

TABLE 4.2
LOCAL EFFECTS GROUND MOTION ARRAYS

Type of Array	Objective		No. Inst.	Flexibility		Desired Intensity	
	Scien.	Data Base		Fixed	Port.	>0.05g	>0.2g
A. Local Laboratory Arrays	**	*	25-40	**		**	*
B. Simple Extended Arrays	*	**	4-12	**	**	**	**
C. Elemental and Special Arrays		**	~3	**	**		**

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should be known about the general nature of the incoming motions to permit assessment of the degree to which these motions are typical.

Simple Extended Arrays

A typical example of a Simple Extended Array is a set of instruments placed across a valley to record the changes in the amplitude and nature of motion at various locations. These arrays will yield a data base on the systematic spatial variations in motion and will permit the testing of simple one-dimensional or two-dimensional theories for predicting such local variations. In general, however, the instrumentation will be inadequate to define the wave propagation through the site and to test complex theories for this effect. Simple Extended Arrays will require 6 to 12 acceleration-measuring devices, usually (but not always) with common time base and simultaneous triggering. Some studies may be accomplished using portable arrays, employing only instruments at ground surface. Others will require fixed arrays, involving some instruments located at depth. Reasonable resolution should be achieved for intensities as small as 0.05g, but good records should also be obtained for strong ground motions.

Fixed Simple Extended Arrays may be located as part of larger fixed arrays for capturing large magnitude events, or may be located by themselves in other areas where there is a high probability of large magnitude events. Section 4.5 presents examples of useful Simple Extended Arrays and gives guidelines concerning their planning and installation.

Elemental Arrays

Examples of Elemental Arrays are vertical arrays or clusters of accelerographs within a limited area (say a diameter of 100 m). These very simple arrays provide a data base concerning the degree of variation of motion with distance and depth. In the case of vertical arrays, the data may be used to test simple one-dimensional theories of ground motion amplification.

Only a few (perhaps three) instruments need be involved in each array and simultaneous triggering and a common time base are not of high priority, although in general they are desirable. These arrays, as well as single instruments, might be used to supplement basic source mechanism arrays and laboratory arrays, or may also be placed in other seismically active areas. Numerous Elemental Arrays already exist in various countries, but as yet few really strong motions ($> 0.2g$) have been recorded. Additional installations of Elemental Arrays would increase the rate at which such information is acquired. Section 4.6 provides guidelines concerning the deployment and use of such instrumentation.

Special Arrays

Two types of special arrays are considered herein: those intended for the study of soil-structure interaction and those dealing with pore-pressure buildup and liquefaction.

Soil-structure interaction: No special arrays for the study of soil-structure interaction are included herein within the initial plans for instrument installation. Once the Local Laboratory Arrays are in operation and have recorded a number of motions, it may be worthwhile to construct simple structures within these arrays in order to test theories for analyzing interaction effects during subsequent shakings. In addition, national groups should be encouraged to install three to five instruments in the free field around selected already-instrumented structures at convenient locations. Section 4.7 elaborates upon these recommendations.

Pore-pressure buildup and liquefaction: It is recommended that simple installations, consisting of one or two acceleration-measuring devices plus several piezometers for the measurement of pore-pressure buildup, be installed in saturated sands at several locations where the expectancy of strong ground motions is high. Priority should be given to medium to dense sands. In the longer run, consideration should be given to the installation of arrays which form field laboratories for the study of liquefaction-related phenomena during actual earthquakes. These matters are discussed in detail in Section 4.7.

4.4 LOCAL LABORATORY ARRAYS

Introduction

The conceptual basis for Local Laboratory Arrays arises from the desire to learn more about the details of the spatial distribution of the seismic excitation within a localized region. Information of this type is needed for the development and confirmation of theoretical models for free-field ground motion analyses, subsequent analysis of nonuniform conditions, and extrapolation to soil-structure interaction situations. Local Laboratory Arrays are intended to provide additional insight into other effects as well, including for example differential and rotational motions.

Local Laboratory Arrays would be located at carefully selected sites. Ideally, these arrays would be situated in such a way as to make use of data from surrounding seismological networks in order to establish the macro-scale free-field environment surrounding the local array.

Objectives

At present, it is possible to list four interrelated objectives of the Local Laboratory Arrays. These are:

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- 1) To measure detailed ground motions over an extensive local zone. Data of this type are desired in the formulation and confirmation of theoretical models which can accommodate seismic wave inputs of various types, frequencies, directions and phasing.
- 2) To determine the relative motions over the region of the array, specifically such quantities as relative displacement, strain (longitudinal and shearing) and rotational motion (torsional and rocking). These types of motion should be obtained for varying base lengths and also at localized instrument stations to the extent possible.
- 3) To secure acceleration data that will be of direct and immediate use in earthquake engineering design as a supplement to existing data. Such information would be additionally valuable in that comparative data will be obtained from relatively closely spaced instruments at the surface and at depth.
- 4) To permit the deployment of newly developed instruments for experimental purposes, i.e. to serve as a testing laboratory to the extent possible.

In order to achieve these objectives the dimensions of a Local Laboratory Array should be of the order of 500 m to 1 km in plan and depth.

Number of Arrays

It is recommended that a minimum goal be three Local Laboratory Arrays possibly in different parts of the world. The establishment of such arrays, in view of their cost, implies a long-term commitment to operation and maintenance, as well as data reduction and dissemination.

An upper limit would seem to be about six such arrays distributed throughout the world. It would be desirable to have some arrays not as permanent as others to enable a shifting of some to better sites as prediction capabilities and general knowledge of seismic sources and attenuation characteristics improve.

Siting

One requirement for siting is that geology and geotechnical properties of the site and its surrounding environs be well known and simple. The latter requirement is important if analysis of the site is to be possible.

Another requirement is that, in so far as possible, the sites should be "typical" so that data obtained can be employed elsewhere by inference. In meeting this goal it is suggested that at least two of the sites have the following general characteristics:

- 1) Uniform Material -- Flat over a 2 km diameter area with uniform material to a significant depth. The value of c_s might range from 200 to 600 m/s in the upper 100 m of depth and increase with depth thereafter.
- 2) Soil over Rock -- Flat over at least a 2 km diameter area with a value of c_s of 200 to 500 m/s in the soil of depth 30 to 100 m. The underlying rock should have a value of $c_s > 1000$ m/s.

Admittedly, it may be difficult to find such ideal sites, but sites possessing these general characteristics should be sought. Special sites involving deep deposits of soft material, or rock over soil, although interesting, will not lead to information of general applicability or simple interpretation. In this connection the arrays, especially those installed initially, should avoid sites prone to significant focusing or dispersion.

The water table can be of some concern in interpreting data. For the uniform site, this level will hopefully be at a depth well below the majority of the instruments.

If possible, the sites should be in sparsely inhabited areas, and certainly not encompass large structures. The desirability of studying soil-structure interaction suggests that instrumented major structures located just outside the array could provide additional valuable information.

With reference to the arrays proposed for source mechanism and wave propagation studies, it is suggested that for the strike-slip and dip-slip faults the first two fixed arrays be located from about 10 km to four focal depths from the fault zone. In this way signals of at least 0.05g can be expected with some reasonable frequency and strong signals from a major earthquake should also be recorded within an acceptable time period.

If, for a single fault system, two Local Laboratory Arrays are possible, a search should be made for geologically different sites. An obvious advantage would arise if the same source mechanism produced detailed records in two different arrays. It would also be advantageous from a siting point of view if an array could be located so as to capture data from several fault systems (one close-in and one at distance).

The selected sites should be examined to be sure that, in the event of seismic activity of great interest, it will be possible to deploy portable instruments around the fixed array to help define the free-field environment surrounding the array.

Example of Local Laboratory Array

In order to provide the reader with some idea of the envisioned scope of a laboratory type array, one possible configuration involving

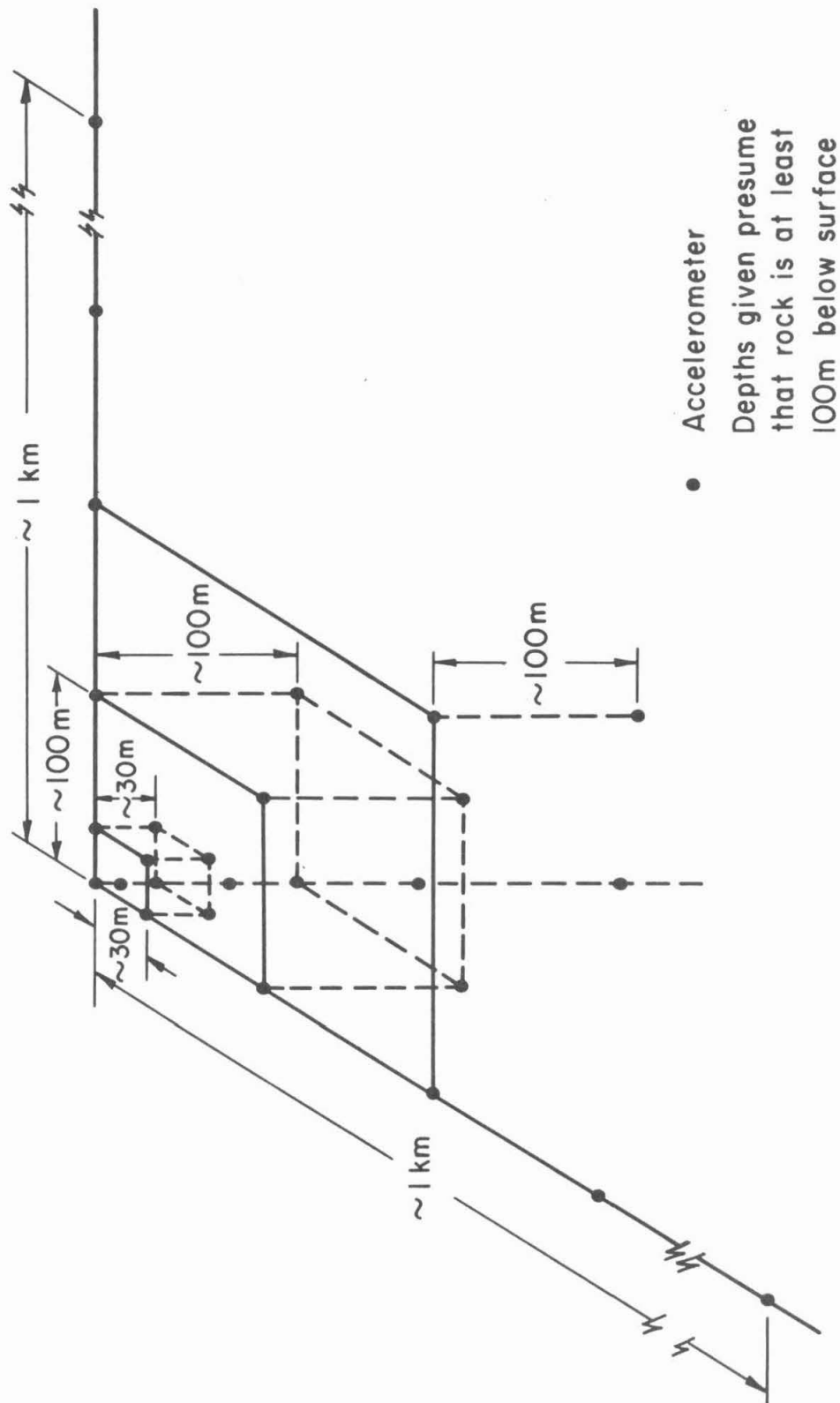


FIGURE 4.1. TYPICAL LOCAL LABORATORY ARRAY CONFIGURATION

twenty seven instruments (accelerometers, for example) is illustrated in Fig. 4.1. This particular array, covering an area of about 1 km², contains two orthogonal strings of instruments on the surface together with down-hole instruments arranged in box array form. The size of the array should be large enough to be representative of the site for a real facility and yet incorporate instrument spacing that will permit identification of the ground wave motions and phasing of the motions traversing the array. The latter objective can only be met if the instruments have a common time base. Other measurements of interest can also be made over the grid, such as relative displacement, strain and rotation.

The exact configuration and number of instruments in any array obviously will require careful study and planning, especially when it is realized that the incoming waves may originate from almost any direction. Indeed it may be that the array configuration should consist of concentric circles of instruments, combinations of linear and arc arrays, etc. It is recommended that both seismologists and earthquake engineers be involved in the detailed design of such arrays.

4.5 SIMPLE EXTENDED ARRAYS

Objectives

These arrays are intended for the study of the influence of local geology and topography on the earthquake motions at different locations. Efforts should be devoted to the definition of individual motions as well as to the determination of relative motions or strains. Three-component instruments, measuring two horizontal and one vertical component of acceleration, are considered in the array schemes proposed herein. However, use of rotational-component instruments should be encouraged, as this would provide additional information of significance in engineering applications.

Many arrays already exist or are planned for the observation of soil amplification effects in horizontally stratified formations (most of them in Japan). Hence, it is felt that no additional arrays need be constructed for this purpose. On the other hand, very few arrays exist for the study of the influence of valleys, surface topography and other local inhomogeneities. Herein attention will be focused on these areas.

Because a main purpose of the effort will be the calibration of simplified engineering models, a few typical configurations are chosen. Although the objective is to consider conditions more general than the stratified formations described above, simplicity will be preserved at this stage. Situations including very pronounced irregularities, such as local faults, have been excluded from consideration.

The final aim of the installation of Simple Extended Arrays is the establishment of criteria to estimate response spectra for practical design applications.

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Value of Data

Experience has shown the influence of irregular geologic and topographic configurations on the local distribution of intensities and damage through focusing, resonance, edge and other effects. The usefulness of the data stems from the possibility of interpreting past observations concerning spatial distributions of intensity and damage, and of establishing conditions under which different models can be applied to predict intensity, assuming estimates are available for the value this variable would have at the site under standard conditions (firm ground, flat topography).

Although the engineers' interest is usually focused on high intensity motions, recording and analysis of low intensity events should be relevant, as a substantial number of records may be required to calibrate engineering models in the linear range of soil behavior. Some degree of extrapolation will probably be required to predict local effects for stronger motions, and that extrapolation should be based on the conceptual models of two-dimensional or three-dimensional response. It should account for nonlinear behavior and not be limited, as has been the previous tradition, to straightforward adoption of amplification functions determined under low strain conditions.

Typical Geologic and Topographic Conditions Requiring Study

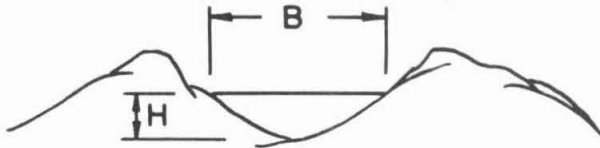
Study of the geologic and topographic conditions shown in Fig. 4.2 is thought to be a good first stage for the generation of a data bank as well as for the formulation and calibration of the next generation of engineering models. Selection of sites including flat topography contiguous to one or more of the other conditions would be advantageous from cost and efficiency viewpoints.

Array Configurations

Typical array configurations are depicted in Figs. 4.3-4.6. Figures 4.3 and 4.4 correspond to narrow and wide valleys, respectively. Arrays in both cases are quite similar. Instrument R is a reference instrument located at some distance from the centerline of the valley. If possible, it might also be an element of a larger source mechanism array. Instrument C would be located at the centerline of the valley in both cases. In the wide valley, S could be a sub-array for study of local effects, its main purpose being that of providing records near the edge region. Instrument I in the wide valley would be intended for the study of the attenuation associated with edge effects.

Figure 4.5 corresponds to a hill or promontory. Here again, R is a reference instrument, located away from the base of the hill. Theoretical studies suggest that motion corresponding to standard conditions is amplified at C and attenuated at A.

a) Narrow valley

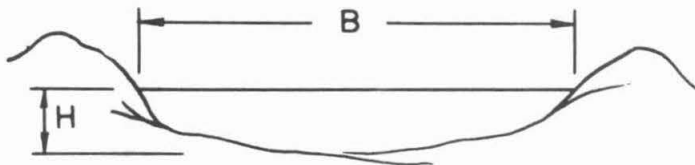


C_s =(shear wave velocity of sediment) 200-400m/s

$B = 300 - 1000\text{m}$

$H = 50 - 300\text{m}$

b) Wide valley

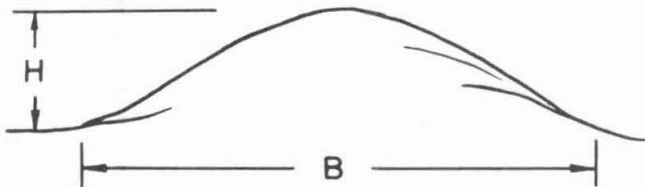


$C_s = 200 - 600\text{ m/s}$

$B > 1000\text{m}$

$H = 50 - 300\text{m}$

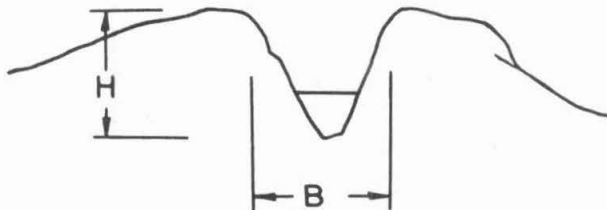
c) Hill



$B = 1000 - 3000\text{m}$

$H = 300 - 1000\text{m}$

d) Deep gorge



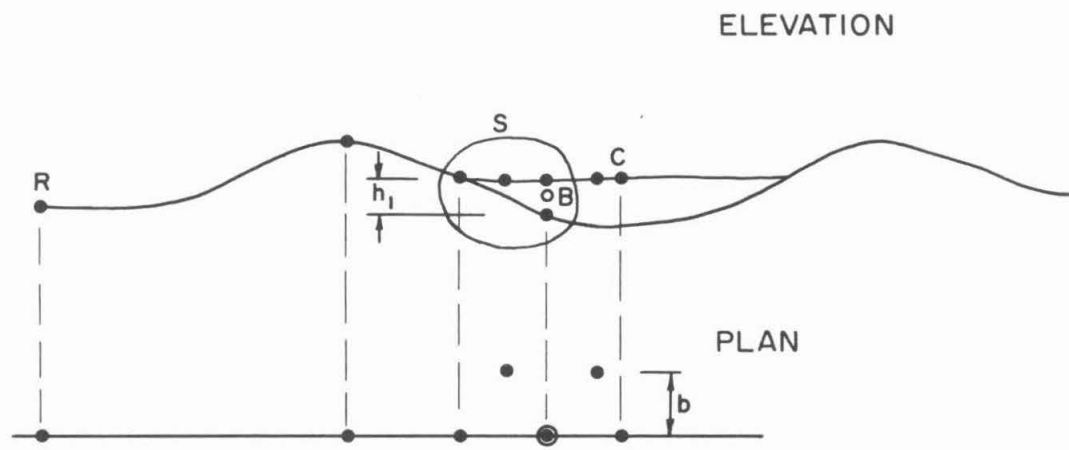
$B = 100 - 300\text{m}$

$H = 100 - 300\text{m}$

e) Flat topography

FIGURE 4.2. GEOLOGIC AND TOPOGRAPHIC CONDITIONS FOR SIMPLE EXTENDED ARRAYS

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- Surface instrument
 - Down-hole instrument
 - R Reference instrument
(If possible, an element of a larger scale array)
 - S Sub-array for study of edge effects
 - B Optional instrument, if response of embedded structures is of interest.
 - C Instrument at center line of valley
- $b, h_1 \approx C_s/4$ ($C_s = \lambda_s$ at 1 Hz)

FIGURE 4.3. TYPICAL SIMPLE EXTENDED ARRAY CONFIGURATIONS FOR NARROW VALLEY

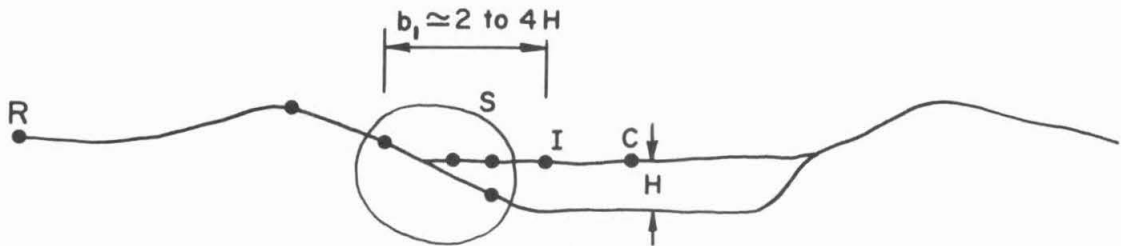


FIGURE 4.4. TYPICAL SIMPLE EXTENDED ARRAY CONFIGURATION FOR WIDE VALLEY

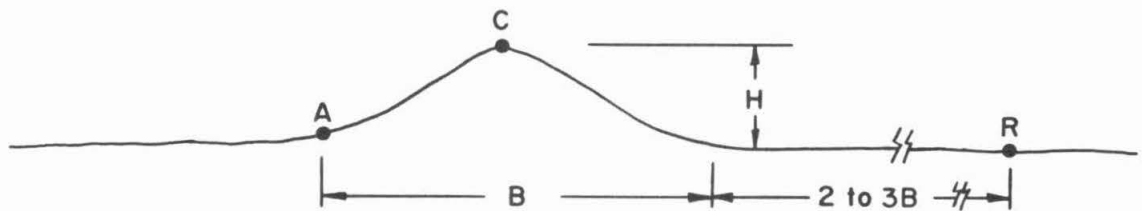


FIGURE 4.5. TYPICAL SIMPLE EXTENDED ARRAY CONFIGURATION FOR HILL OR PROMONTORY



FIGURE 4.6. TYPICAL SIMPLE EXTENDED ARRAY CONFIGURATION FOR DEEP GORGE

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Figure 4.6 corresponds to a deep gorge. The proposed instrumentation deployment is similar to that for a hill or promontory. The array configurations shown in Figs. 4.5 and 4.6 are minimal. Installation of one or more down-hole instruments in each case would provide very significant information for the calibration of two-dimensional models of dynamic response.

Another important case is that of linear surface arrays intended for the study of out-of-phase motions and strains for the purpose of the design of pipeline and extended-in-plan systems. Five to ten instruments are envisaged, placed along straight lines. The orientation of those lines as well as the spacing between instruments should be decided upon in terms of dominant expected wave types, their direction of propagation and their lengths for the frequencies of interest in engineering. Variable spacing might be adopted, but along at least one half wavelength that spacing should not exceed $1/8$ wavelength.

Instrument Requirements

The above array configurations refer to permanent installations of commercially available strong-motion accelerographs. For most purposes, adequate resolution can be obtained with analog devices. Triggering levels should be of the order of 0.01 to 0.02g, but only those records containing accelerations greater than 0.05g are deemed to lead to sufficiently accurate spectral curves. More accurate instruments, and specifically instruments where the initial portion of each record is not lost, may be indicated for the purpose of determining relative displacements and strains.

In addition to the instruments required in the configurations described above, two or three semi-permanent instruments, of the same type as the rest, should be included in each array and eventually relocated within the array if the information obtained from initial observations makes such a change advisable.

Value of Instruments at Depth

Information obtained from down-hole instruments is significant for its own sake and for its applicability to the calibration of engineering models. In particular, such information is valuable for the following reasons:

- 1) The variability of motion on bedrock over relatively small distances is important for the design of many extended-in-plan structures.
- 2) The design of some embedded structures is based on amplitude and frequency content descriptions of motions at various depths.

- 3) Knowledge of simultaneous motion at and below the surface can be used to suggest models for general patterns of wave propagation in the vicinity of the site, and serve to calibrate existing and new models.

Wherever practical down-hole instruments should be added to local effects arrays.

Processing and Analysis of Data

Data obtained from Simple Extended Arrays may be used in the following manners:

- 1) As a source of direct knowledge on the distribution of motion for different configurations. The distribution may be expressed in terms of the comparison of spectral functions as well as of cross-correlation functions of accelerations.
- 2) As a basis for calibrating existing models, for improving them or for developing new ones. Calibration of simplified two- and three-dimensional wave propagation, finite element and absorbing boundary models, is foreseen as a natural outcome of the arrays output.

Common Triggering and Time Basis

Because knowledge of arrival times and phase differences would be of significance in the analysis schemes described above, it is recommended that all instruments be equipped with appropriate devices to provide a common time base. Moreover, they should operate in a master-slave mode, with the master being the most easily triggered instrument.

Interfacing with Larger Scale Arrays

The influence of local conditions strongly depends on the types and directions of incoming waves. Hence, knowledge of the general pattern of energy travel from source to site is very relevant to engineering models for study of local effects. As a consequence, it is recommended that at least one of the rock-site stations of each Simple Extended Array be located away from irregularities and correspond to one station belonging to an array intended for studies of wave propagation on a larger scale.

4.6 ELEMENTAL ARRAYS

This section is concerned with those configurations of instruments designed to provide data on local effects but not included within Local Laboratory Arrays or Simple Extended Arrays. These Elemental Arrays are intended to answer questions of engineering significance and will be

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configured in different ways according to the local conditions, presence of other instruments, and technical questions to be investigated.

Two typical situations calling for the installation of Elemental Arrays are: 1) the establishment of a permanent array to measure source mechanisms for large events, and 2) measurement of significant seismic motions in an area not covered by other arrays. In the first case, the additional Elemental Arrays would be intended to supplement the data on the source mechanism with additional data on local effects of engineering importance. In the second case the additional effort would involve tying together the strong-motion instrumentation in such a way as to maximize the value of data obtained in an earthquake even though the site is outside the range of a Local Laboratory Array or a Simple Extended Array. Because such Elemental Arrays are relatively inexpensive, they can be distributed widely, and the chances of picking up useful data from strong earthquake motions is correspondingly increased.

Types of Elemental Arrays

Several types of Elemental Arrays should be developed. These include:

- 1) Arrays of three strong-motion accelerometers located on the ground surface in the corners of a triangle with each leg approximately 50 m long. The accelerometers must be simultaneously triggered and have common time bases. Such arrays would provide data on local wave propagation effects and local relative motions.
- 2) Arrays of two accelerometers in which one instrument is located on either a rock outcrop or in deep rock and the other on soil. These would provide data on soil amplification effects. Common triggering or timing would improve the quality of the theoretical interpretation of the records. Such arrays could be part of a larger array used for other purposes.
- 3) Strong-motion accelerometers located at depths less than 100 m in alluvium and near other surface mounted instruments that are part of a larger array. The typical case would be in conjunction with the large arrays proposed for measuring strong-motion effects near the causative fault. Such causative fault arrays would be placed on the surface, and these additional instruments would be placed at depth to measure local amplification effects.
- 4) Arrays of instruments located on the surface at distances of several kilometers around Local Laboratory Arrays. These would provide data on the patterns of motion travelling toward the laboratory. Common timing is essential.
- 5) Arrays located on or near structures. Many arrays or sets of single instruments have been installed near or on structures.

These would be much more useful if they were arranged into simple arrays with some instruments in the free field and some on the structure and with common timing and triggering.

Array Locations

The Elemental Arrays described above are relatively simple and inexpensive to install. They can be deployed with currently available technology. Nevertheless they would provide highly useful data on local wave propagation and focusing effects that are the subjects of much concern and controversy in earthquake engineering.

Some twenty eight areas have been identified in this report as likely to experience strong shaking in a decade of observation. While decisions are being made about where to install the large expensive arrays such as those required for source mechanism and wave propagation studies, and while funding and approvals are being sought, small Elemental Arrays should be installed in as many of the likely areas as possible.

Elemental Arrays should also be located around the site of any Local Laboratory Array. They should be associated with and be supplementary to the arrays established to observe source mechanisms. Existing strong-motion instrumentation could be effectively supplemented by Elemental Arrays.

Instrument and Other Requirements

In general, Elemental Arrays should consist of commercially available strong-motion accelerometers. They may require provisions for common timing or triggering so that patterns of wave motions or coherence can be observed. Some special purpose instruments or instruments that are at this time still under development may be deployed along with these arrays, but the basic constituents of the arrays must be dependable, proven devices.

In order to obtain data on relative motion between points it would be highly desirable if accelerometer records could be differenced electronically and the differential record output on tape.

The geological and geotechnical characteristics of the site should preferably be known before the instruments are installed. When the array is associated with structures, the dynamic characteristics of the structures, as well as the engineering plans, should also be available before the instruments are installed.

Sponsorship

Elemental Arrays could be installed under a variety of sponsoring arrangements. Where Local Laboratory or Source Mechanism Arrays are

LOCAL EFFECTS ARRAYS

installed, the complementary Elemental Arrays should be included in the plans and in the funding. Some other arrays could be developed as part of a national or local program of strong-motion instrumentation. The latter situation involves essentially making the strong-motion instrumentation more useful by tying the instruments together and planning their location.

4.7 SPECIAL ARRAYS

Soil-Structure Interaction

One example of the value and practical application of information obtained from a Local Laboratory Array is a quantitative understanding of typical soil-structure interaction phenomena. Records obtained from this type of array as a result of one or more sizable earthquakes would establish the precise field of motion expected at the site for subsequent earthquakes. Typical simple structures could then be constructed within the array site, appropriately instrumented and observed during later earthquakes.

Interpretations of the extensive data base obtained from the envisioned soil-structure interaction experiments along with confirmatory theoretical analyses are expected to identify simple free-field arrays (perhaps one instrument) and essential structural arrays (perhaps one or two instruments) actually required for practical interaction of situations. This knowledge could then be applied to the instrumentation of a number of real structures in high seismicity areas of the world, along with free-field instruments if necessary, in order to gather a meaningful collection of data on the earthquake response of existing structures. The structures used in such studies should have clearly defined properties so that their response behavior can be easily interpreted.

Three structural types are considered as possible test beds for Soil-Structure Interaction Arrays: 1) A prototype rigid foundation of low mass, 2) a one-tenth scale simple structure with a rigid foundation and a massive superstructure, and 3) an extended linear structure buried in soil.

Prototype rigid foundation: This could be a rigid reinforced concrete box or cylinder about 40 meters in plan and embedded in soil to a depth of some 20 meters. The box should have the same translational and rotational inertia as the displaced soil. Instrumental arrays attached to the prototype should include:

- 1) Translational and rotational accelerometers of the same type as used in the Local Laboratory Arrays (four instruments)
- 2) Extensometer probes extending into and anchored to the soil along the soil-structure interface area (20 instruments).

Model structure: The 1/10th scale model structure should have a simple shape and be placed directly on the soil surface as indicated in Fig. 4.7. Instruments attached to the model structure would include:

- 1) Translational and rotational accelerometers on the rigid foundation and massive superstructure (four instruments)
- 2) Dynamic strain gauges on structural elements (24 instruments)
- 3) Dynamic earth-pressure meters under the rigid foundation (four instruments).

Extended linear structure: The extended linear structure could be a continuous thick-walled steel pipe, buried in a horizontal plane through a Local Laboratory Array and so oriented as to maximize the differential motion of the pipe as the wave passes the linear structure. The pipe should be proportioned to provide significant bending and shear stiffness contrasts between the surrounding soil and the pipe. The pipe should be provided with interior strain gauges (about 40) and exterior extensometers (about 20). In addition to these instruments, a number of accelerometers (about 10) should be installed along the length of the pipe to measure wave propagation along the pipe and to assess the attenuation of free-field motion due to the presence of the pipe.

Data processing: All accelerometers, extensometers, strain gauges, and earth pressure meters for soil-structure interaction studies should have the same sensitivity, resolution and recording requirements as the Local Laboratory Array instruments. Data reduction and processing should also be the same.

Liquefaction and Related Phenomena

The primary purpose of the proposed arrays is to obtain accelerations and pore-pressure histories at suitable locations within deposits of saturated or partially saturated soils, especially medium and dense sands.

Two levels of array sophistication appear to be useful for the study of *in situ* liquefaction phenomena. The first level would provide basic information at minimum cost and array complexity. This array level could be easily sited with a minimum program of local soil investigation. The second level of array sophistication is more desirable but requires greater complexity and expense, more site investigations, and is applicable to sites having particular geological characteristics.

Small liquefaction arrays: The simplest array for *in situ* liquefaction studies would consist of one or two strong-motion accelerometers and one or two piezometers placed at different depths in the same borehole. One of the accelerometers would be anchored at the ground surface and the piezometer(s) placed in a sealed borehole. Simultaneous records

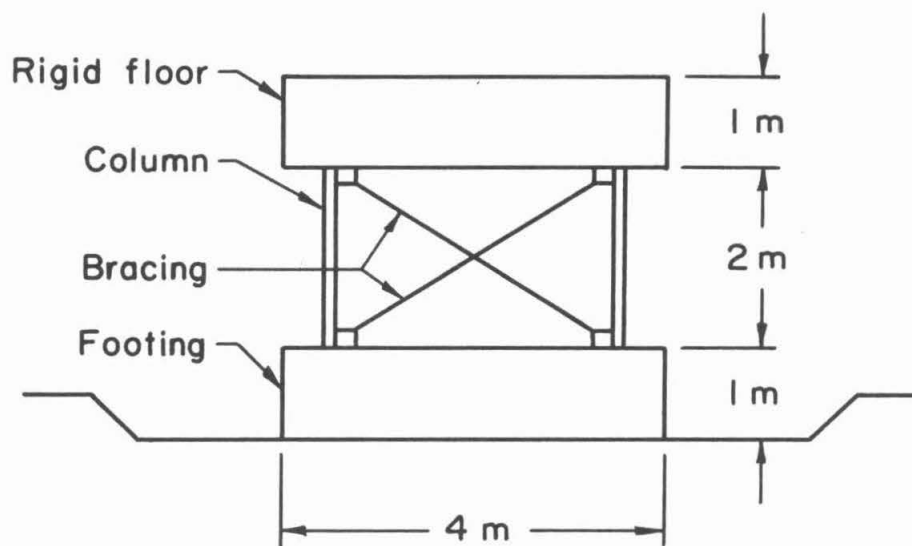


FIGURE 4.7. BASIC STRUCTURE FOR INTERACTION STUDIES

of the time histories of pore pressures and the ground surface acceleration should be made.

Small liquefaction arrays should be sited in a geologic environment that includes a saturated sand stratum at least three meters in thickness and located at a depth of no more than 15 m. The priorities of sand densities in the stratum to be instrumented are: 1) medium, 2) medium to dense, and 3) loose to medium. Loose sands should be avoided because of the risk that ground failure and sand boils would disrupt the instrumentation. The minimum strong-motion surface acceleration potentials for this type array should be 0.10 to 0.15g for sands of medium density, more than 0.20g for medium to dense sands and 0.05 to 0.10g for loose to medium sands.

Research liquefaction arrays: Whereas most people today recognize that current field tests, laboratory procedures, and numerical and analytical techniques are able to identify the danger of liquefaction for loose deposits, great uncertainties exist for the case of medium and dense sands. This situation and the somewhat conflicting views existing on this issue have favored the adoption of strongly conservative design approaches to the problem, with economic implications that can be particularly significant in large scale projects. Since experience has shown that laboratory tests results are doubtful and can be made to fit quite different theories, it is felt that a decisive step can only be achieved by direct *in situ* observations. The envisaged special arrays would help to gain a better understanding of:

- 1) The correlation between liquefaction potential and *in situ* geotechnical properties (e.g., penetration resistance, stratigraphy, grain size distribution, etc.) of a given sandy soil;
- 2) The process of spatial diffusion of liquefaction as a function of the soil geotechnical properties and stratigraphic configuration and the largest depth at which liquefaction can occur in a given deposit;
- 3) The correlation between pore pressure and acceleration histories, the latter being the key variable used in liquefaction analyses;
- 4) The development and dissipation of earthquake induced pore pressures in a given deposit from a three-dimensional viewpoint.
- 5) The validity of theories for predicting the generation of excess pore pressure and its dissipation after the end of ground motion, with related drainage path effects.

It is anticipated that the interpretation of a few sets of records from a well located array might bring about significant changes in current methods for assessing the likelihood of liquefaction.

Research liquefaction arrays would consist of a number of boreholes with several instruments each. A possible arrangement is shown in Fig. 4.8. Since maximum liquefaction depths are of the order of

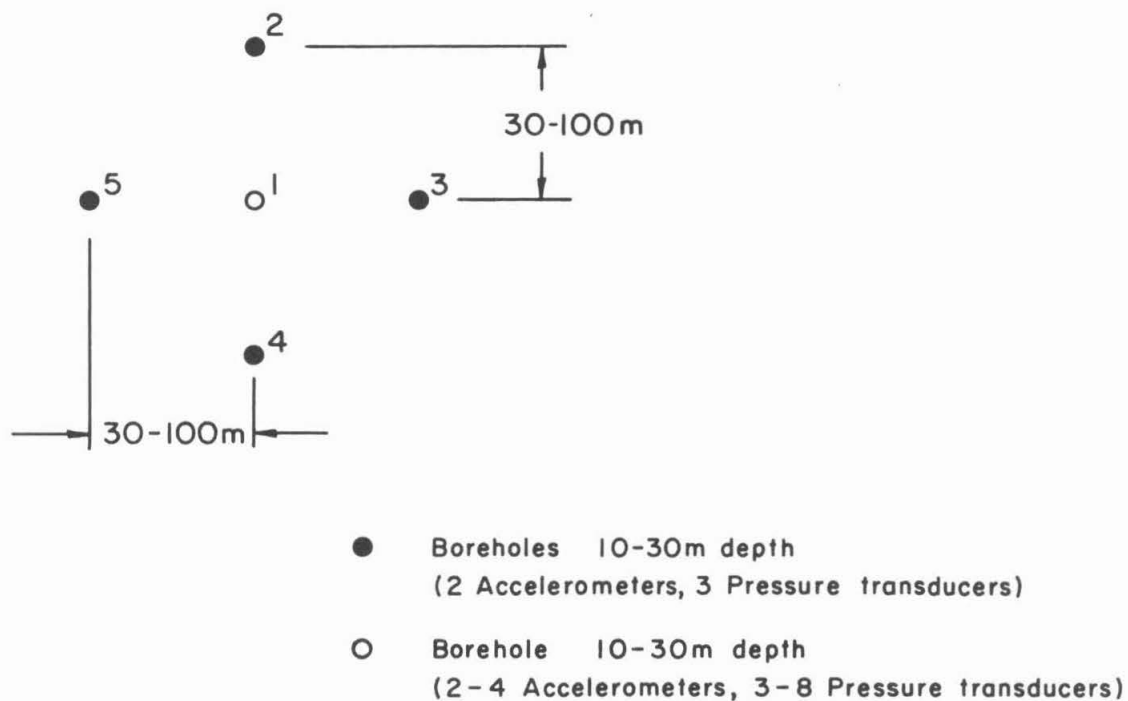


FIGURE 4.8. TYPICAL RESEARCH LIQUEFACTION ARRAY CONFIGURATION

20-30 m, the depth of the boreholes should typically span between 10 and 30 m; the bottom of the boreholes roughly coinciding with the lower boundary of the potentially liquefiable soil formation. Each of the peripheral boreholes of such an array (Nos. 2 to 5) should carry two accelerometers (one at the top and one at the bottom), and perhaps three pore-pressure transducers (two at the same points as the accelerometers and one at mid-depth). The central borehole should carry one or two additional pore-pressure/accelerometer packages at intermediate points (typical spacings of 3 to 6 m) in order to monitor in greater detail time histories as a function of depth.

All of the instruments in a research liquefaction array should have a common time base, chiefly in order to allow correlation of pore-pressure histories at different boreholes and pore-pressure and acceleration histories at the same borehole. Operation in a master-slave mode should be envisaged, with one of the surface accelerometers acting as a master or reference instrument.

Priority in site selection should be given to extended ($\sim 1-2 \text{ km}^2$) deposits of saturated, sandy soils, possibly with significant trends of variation of average densities in the horizontal direction. Ideally this should permit placing one array at a location having medium sands, one at a location having dense sands, and perhaps one where loose sands are present. Consideration should also be given to large scale deposits (tens of km^2) in the vicinity of active seismic sources, where several arrays could be installed in order to monitor dynamic pore pressure phenomena both as a function of focal distance and local geotechnical properties. Correlation between data from different liquefaction arrays could be provided by their having a common absolute time base.

Because of their characteristics, these research liquefaction arrays can only be intended as permanent installations. It is also evident that an adequate site selection requires relatively careful geotechnical exploration. A reasonably detailed stratigraphic description is needed, together with determination of standard (or equivalent) penetration resistance and grain size distribution as close as possible to the instrument locations. Permeability tests would also prove valuable. Careful monitoring of water table level is important.

Instrument characteristics: As it is desirable to obtain data over a large range of ground shaking intensities, say from $0.02g$ to several tenths of a g , use of force-balance acceleration transducers is suggested. The same type of sensor should be employed at both the surface and down-hole locations. Flat frequency response up to 25-30 Hz is required.

Strain gauge type pressure cells and pieze-resistive pressure devices are available for dynamic pore pressure measurements. Some development work is anticipated in order to couple such sensing units with strong-motion recording units. The overall frequency response of the pore-pressure instrumentation should be comparable to that of the accelerometers. Valuable information on the characteristics and anticipated performance of pore-pressure devices has been obtained in connection with the Rio Blanco underground nuclear test. Special care is required for impedance-matching aspects in the down-hole installation of these units.

LOCAL EFFECTS ARRAYS

Analog recording systems are considered adequate, provided an overall dynamic range of 50-60 dB can be attained. However, more study appears necessary to better define this aspect of the problem.

Analysis and interpretation of data: In seismic pore-pressure histories it could be useful to look separately at the "sustained" increase-decrease trend, and at the superimposed high frequency signal. Hence, adequate provisions should be made for standard bandpass filtering to separate the sustained component. Typical sampling rates of 100 samples/sec appear adequate for most applications, both as regards acceleration and pore-pressure signals. The need for performing relatively sophisticated analyses such as cross-correlations between signals recorded at different points is anticipated. Other processing techniques are likely to evolve from specific studies, as data of this type become available.

Useful information on the correlation between, for example, peak ground acceleration and peak excess pore pressure can be obtained starting from shaking levels as low as 0.05g and less than ten significant cycles of motion. Hence, location of the proposed special arrays should give priority to sites where there is frequent occurrence of events in the 0.05-0.10g acceleration range, and relatively high probability of accelerations greater than 0.2g in the near future.

Interfacing with other arrays: Efforts should be made to locate all liquefaction arrays as close as possible to accelerometer stations which are on competent ground (rock, firm soil) and which belong to a larger-scale array devoted either to regional wave propagation studies or to source mechanism studies. The source mechanism array seems to be more promising because experience has shown that the chances that significant pore-pressure phenomena will occur are very high whenever deposits of saturated sandy soils are present within the epicentral area of a strong earthquake. Furthermore, sites near the epicenter will experience the strongest shaking and, hence, the greatest potential for development of excess pore pressures. A detailed knowledge of the patterns of motion input to the soil will improve the understanding of the phenomena involved in cyclic loading. Data on the behavior of the soil could be useful to studies of seismic wave propagation as well.

4.8 DEPLOYMENT CONSIDERATIONS

This section discusses the possible composition of a total package of instruments for measuring local effects. Two levels of installation are considered:

- Level I: An optimum level, representing an appropriate balance between effectiveness and cost.
- Level II: A minimum level, below which the effectiveness of the installation would fall off sharply.

The particular configurations presented are illustrations only; actual details must be chosen to fit the particular situation. The use of portable arrays is also discussed.

Local Effects Instrumentation as Part of Source Mechanism Arrays

The source mechanism arrays discussed elsewhere in this volume are intended to record the very strong motions near (within 20 km) the fault break associated with large earthquakes. Most of the instruments in such arrays will be sited on rock. These arrays should by themselves yield data which earthquake engineers have long desired. At the same time, the opportunity to obtain other much needed data should not be overlooked. The following guidelines should be considered:

- 1) For magnitudes greater than 7.0, and especially greater than 7.5, there is a need to measure strong motions to distances greater than 20 km from the fault. Additional instruments should therefore be placed along lines extending out from the fault to a considerable distance. Data from these additional instruments, together with those from the instruments in the basic array, will permit greater accuracy in the measurement of attenuation relations. Simultaneous triggering of the additional instruments is not necessary.
- 2) In conjunction with some of the source mechanism instruments installed on rock, additional instruments should be placed nearby on soil to provide data as to how soil modifies really strong motions. Priority should be given to sites located closest to the fault, and spaced along the fault.
- 3) Several Simple Extended Arrays should be placed in connection with source mechanism array instruments installed on rock. They will give important data concerning horizontal variation of ground motions across different formations, at strong motion levels.
- 4) Other instruments should be installed in cities within 50 km of the fault containing significant engineered structures, and near selected special structures such as large dams. In addition, one or more Local Laboratory Arrays and several liquefaction arrays should in general be included.

Table 4.3 indicates the instrumentation which should be added to a typical source mechanism array for the sake of collecting data concerning local effects. Table 4.4 suggests the deployment for the instruments comprising the Elemental Array category. Note that no research liquefaction arrays are included, primarily because more planning and research is required for the design of such arrays. It is, however, recommended that such arrays be installed in the future.

Strike-slip fault: Figure 4.9 illustrates the principles of deployment discussed above for a strike-slip fault mechanism. The solid points represent instruments which might be part of a source mechanism array. For purposes of studying attenuation, a string of instruments should be extended out to 150 km on each side of the fault at the mid-point of the source mechanism array. The figure illustrates possible locations for Local Laboratory Arrays, Simple Extended Arrays, and small liquefaction arrays and other instruments falling under the category of Elemental Arrays.

TABLE 4.3

LOCAL EFFECTS ARRAYS TO BE ADDED
TO SOURCE MECHANISM ARRAYS

Fault type	<u>strike-slip</u>		<u>subduction</u>		<u>dip-slip</u>	
	I	II	I	II	I	II
Local Laboratory Arrays						
No. of arrays	1	1	1	1	1	1
Total No. of accel.	30(15)	26(13)	30(15)	26(13)	30(15)	26(13)
Simple Extended Arrays						
No. of arrays	2	-	2	-	1	-
Total No. of accel.	12(3)	-	12(3)	-	8(2)	-
Elemental Arrays						
Total No. of accel. (see Table 4.4)	20(1)	11	14(1)	10	12(1)	10
Simple Liquefaction Arrays						
No. of arrays	2	-	2	-	2	-
Total No. of accel.	2(4)	-	2(4)	-	1(2)	-
Total No. of piezo.						
Total No. of instruments	68(23)	37(13)	62(23)	36(13)	53(20)	36(13)

() denotes instruments placed at depth.
 These numbers do not include allowances for non-functioning instruments.

TABLE 4.4

ELEMENTAL ARRAYS AND INSTRUMENTS TO BE
ADDED TO SOURCE MECHANISM ARRAYS

Fault type	<u>strike-slip</u>		<u>subduction</u>		<u>dip-slip</u>	
	I	II	I	II	I	II
Level of effort						
Individual accelerographs to observe attenuation	10	5	4	4	6	4
Instruments on soil in conjunction with source mechanism array instrument on rock	4(1)	3	4(1)	3	3(1)	3
Individual accelerographs near engineered structures	6	3	6	3	3	3
Total No. of instruments	20(1)	11	14(1)	10	12(1)	10

() denotes instruments placed at depth.
These numbers do not include allowance for non-functioning instruments.

LOCAL EFFECTS ARRAYS

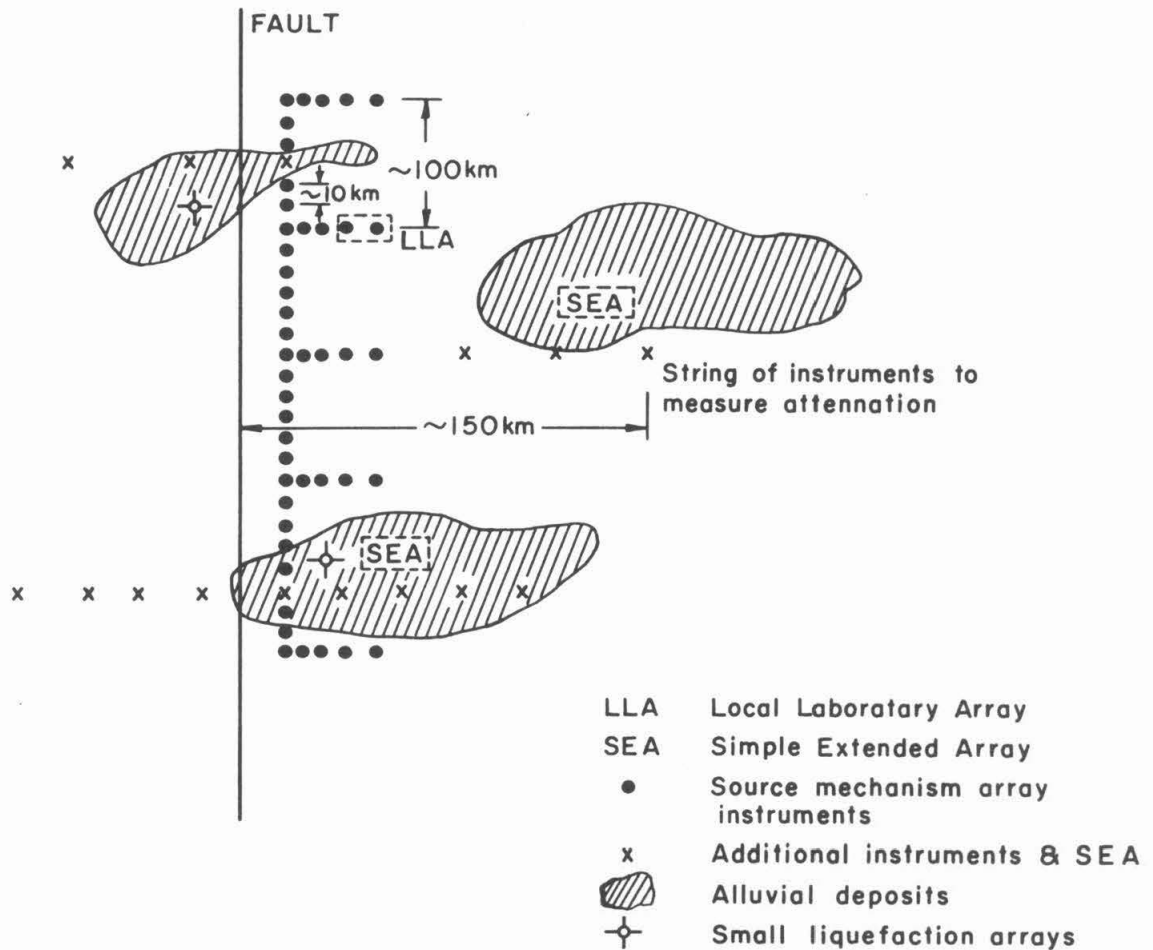


FIGURE 4.9. DEPLOYMENT OF LOCAL EFFECTS ARRAYS WITH SOURCE MECHANISM ARRAY FOR A STRIKE-SLIP FAULT

Subduction faults: The same general deployment strategy outlined above applies for subduction faults, except that in general no instruments would go on the submerged side of the fault. If, in the future, satisfactory instrumentation for submerged operations is developed, it would be desirable to add such devices to either then-existing or still planned arrays.

Dip-slip faults: The configuration of source mechanism arrays for dip-slip faults about 50 km long is sufficiently different from those proposed for long strike-slip faults or subduction zones that the Simple Extended Arrays and Elemental Arrays associated with the source mechanism array should also be different. In this case the source mechanism array will be a grid some 50 km on a side. This should provide a fairly good picture of the attenuation phenomena on rock. Additional arrays should consist of:

- 1) Instruments or Elemental Arrays located 50 and 100 km from the fault to provide data on attenuation beyond the source mechanism array. These should be on both sides of the fault.
- 2) Instruments or Elemental Arrays located on soil within the source mechanism array.
- 3) One Simple Extended Array at an appropriate valley or alluvial site.
- 4) One Simple Liquefaction Array.

It may also be desirable to locate a Local Laboratory Array within the source mechanism array, but this depends on local geology and site conditions. Figure 4.10 shows a typical configuration.

Local Effects Measurements Independent of Source Mechanism Arrays

Because of the complexity and expense of installing and maintaining source mechanism and wave propagation arrays, such arrays will be uncommon. Strong motions will occur in many areas of substantial seismic risk that are not covered by such intensive instrument arrays, and data from these events could be captured by deploying Simple Extended Arrays and Elemental Arrays in these areas. Furthermore, local and national authorities may wish to install these simpler arrays as a means of improving local earthquake engineering design practice. With international cooperation, the design of these arrays could be improved and the information exchanged. Details of the deployment of such arrays will vary from location to location.

Minimum installation: A minimum deployment plan would consist of approximately 20 standard accelerographs installed in the vicinity of each of the 28 promising sites identified in this volume. These instruments might be deployed as suggested in Figure 4.11. A given installation would include (see Table 4.5):

LOCAL EFFECTS ARRAYS

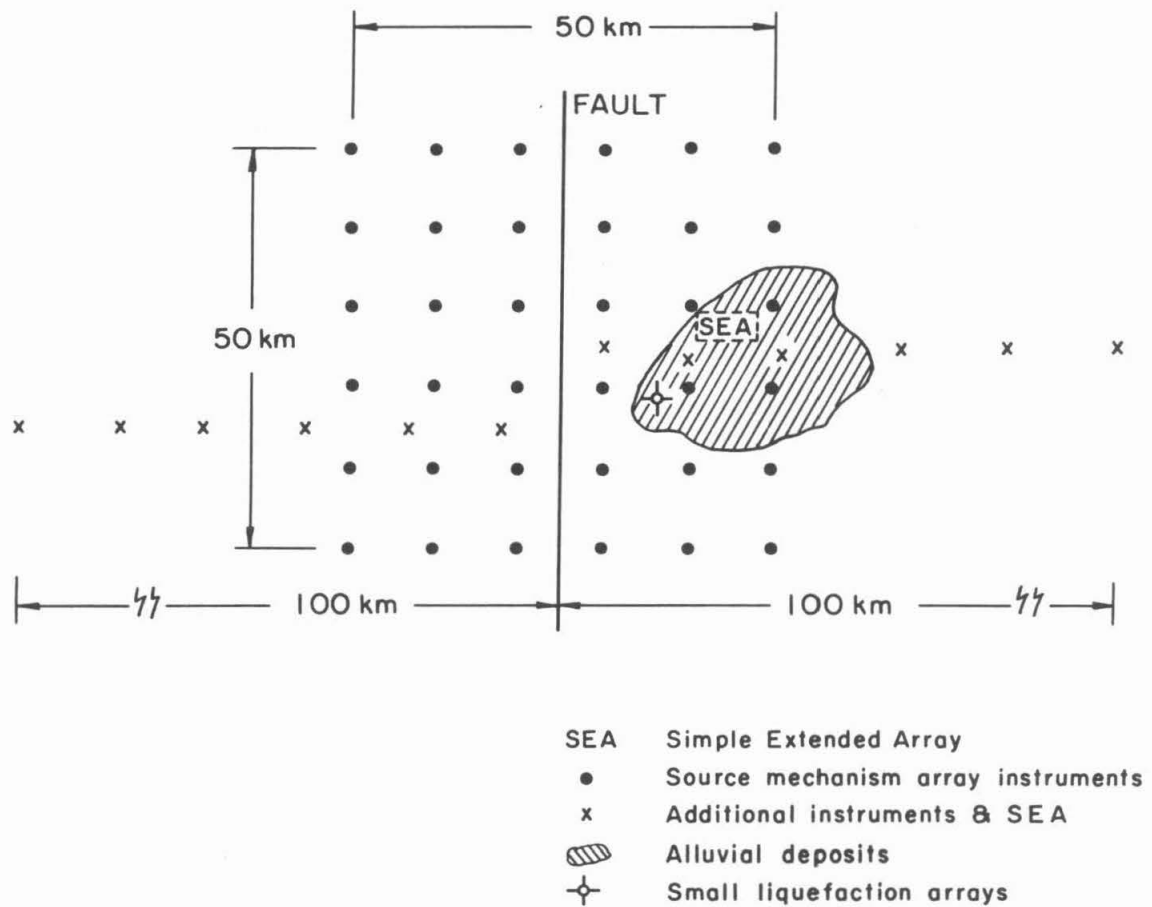


FIGURE 4.10. DEPLOYMENT OF LOCAL EFFECTS ARRAYS WITH SOURCE MECHANISM ARRAY FOR DIP-SLIP FAULT

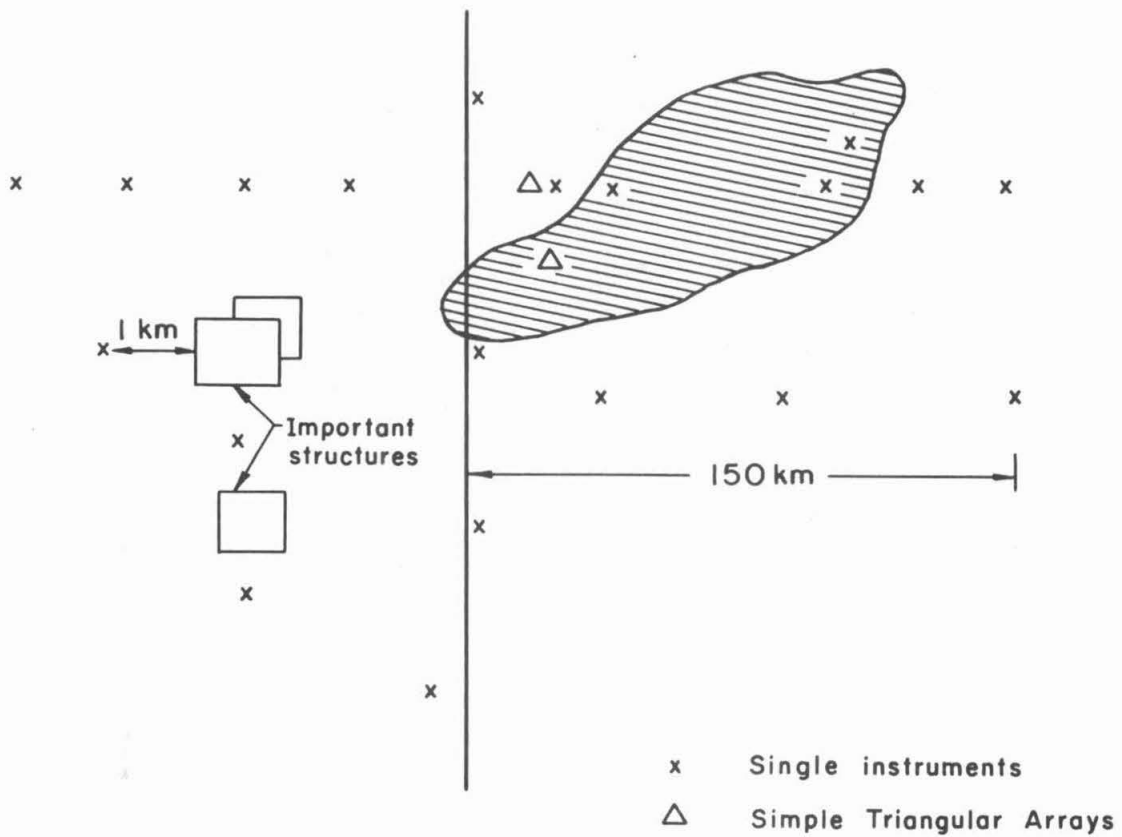


FIGURE 4.11. MINIMUM INSTALLATION FOR STAND-ALONE LOCAL EFFECTS ARRAYS

TABLE 4.5

LOCAL EFFECTS INSTRUMENTATION FOR FAULTS
WITHOUT SOURCE MECHANISM ARRAYS

NUMBER OF INSTRUMENTS REQUIRED

	<u>Minimum Effort</u>	<u>Optimum Effort</u>
Attenuation studies	10	20
Soil amplification studies	3	4
Simple Extended Array	-	8(2)
Soil-structure Interaction Array	3(3)	6(3)
Simple Liquefaction Array	-	3(2)
Elemental Arrays	6*	28(15)
Total No. of instruments	22(3)	69(22)

*Two simple triangular arrays.
() denotes instruments placed at depth.

STRONG-MOTION ARRAYS

- 1) Six instruments to record motions with distance away from the fault, so as to define attenuation relationships. These would preferably be on rock.
- 2) Four instruments deployed along the fault and close to it to capture any extremely large ground motions that might occur. These too would preferably be sited on rock.
- 3) Three instruments on soil sites adjacent to instruments on rock.
- 4) Three instruments located near structures of engineering interest.
- 5) Two or more Elemental Arrays of three units each arranged in a triangle with legs 50 m long. These should be on different geologic settings and should be sited on soil.

Improved installation: Some nations may wish to improve upon these minimum installations. The instruments of an improved installation might be deployed as suggested in Fig. 4.12. Improved installations would involve (see Table 4.5):

- 1) One or more sets of strong-motion accelerometers located at distances between 10 and 150 km from causative faults in order to obtain data on attenuation.
- 2) One or more Simple Extended Arrays for study of local wave propagation.
- 3) For favorable locations, one Local Laboratory Array and one small liquefaction array.
- 4) Instruments on or near engineered structures.

Mobile Instrument Arrays

Aftershock sequences provide unique opportunities for obtaining a number of records of motions with different magnitudes originating from a fairly localized source. Although there will certainly be some difference between the local effects observations corresponding to various magnitudes and hypocentral distances, determination of these effects at smaller intensities is still of significant value. Hence, deployment of surface arrays or portable instruments in the aftershock area of large earthquakes is strongly recommended. Each array should include about 10-20 accelerographs. Detailed siting considerations should follow the principles stated above for permanent instrument arrays. Common triggering will in general be required, as the influence of local conditions may lead to great differences in motion intensities at different points during the same shock.

Mobile arrays will be especially valuable when deployed after a major earthquake has occurred on one of the faults instrumented by a

LOCAL EFFECTS ARRAYS

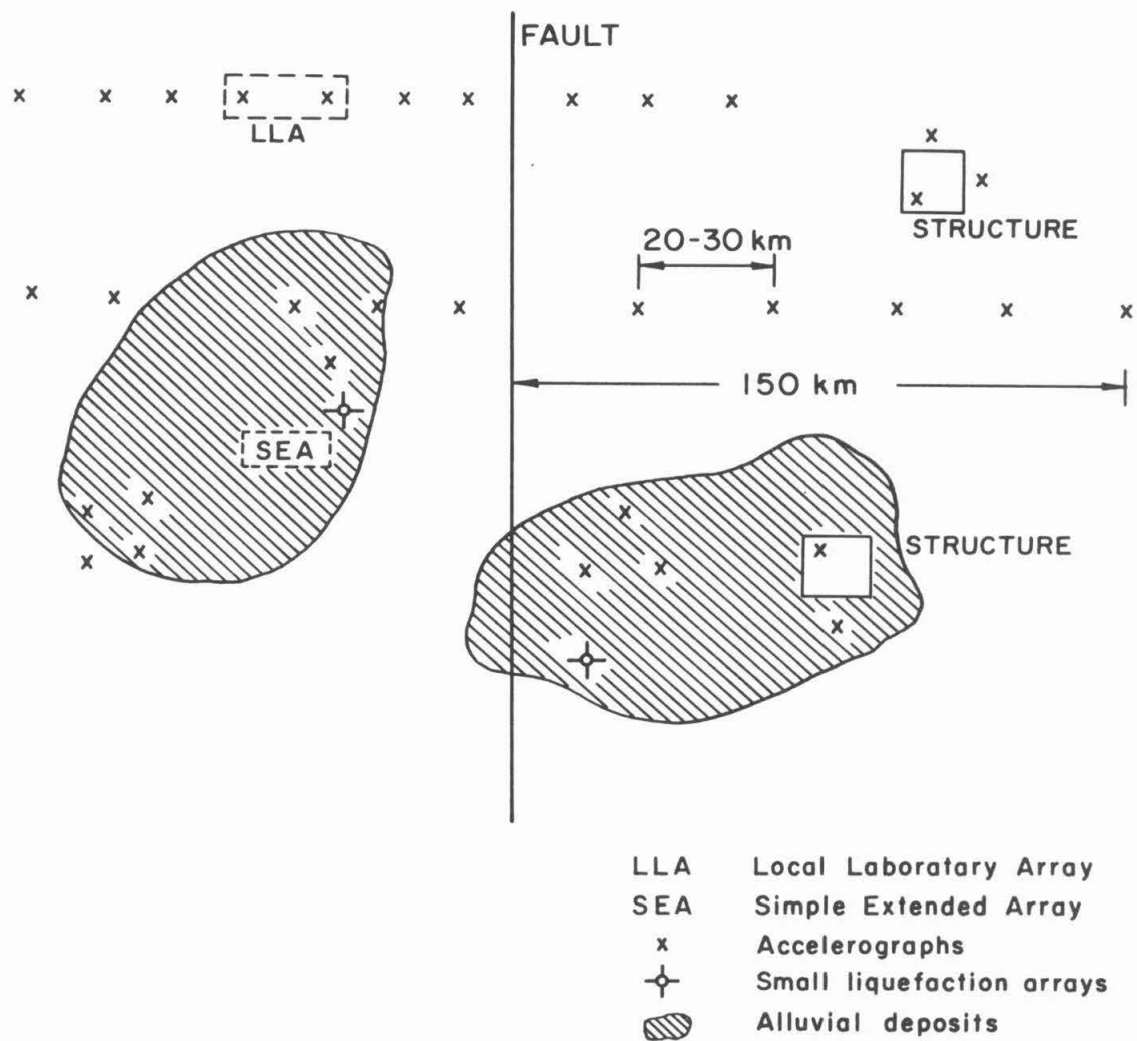


FIGURE 4.12. IMPROVED INSTALLATION FOR STAND-ALONE LOCAL EFFECTS ARRAYS

source mechanism array, and when operated in conjunction with wave propagation investigations also using mobile instruments. It is important however that some 10 to 20 instruments be specifically earmarked for local effect studies and be under the control of engineers.

Design of Data Processing and Analysis System

The design of software is as important as the design of hardware. Some stages of data processing can rely on adequately designed hardware, but advanced analytical procedures and software are needed to reach definite conclusions in particular cases. Hence, at least one standard data processing and analysis procedure should be established along with the design and specification of each array.

A standard data processing procedure should specify the following:

- 1) Sampling time interval
- 2) Characteristics of band-pass filter for pretreatment of data
- 3) Duration of recording or number of data points
- 4) Characteristics and limitations of algorithms employed for data analysis such as correlation function, power spectral density, coefficient series for auto-regressive models, etc.
- 5) Allowable limit on signal to noise ratio for both continuous wave and pulse type noise.

The development of software may require significant funds in addition to that for construction of the array. On the other hand, independent designs of hardware and software may cause much confusion in future use of the results of these experiments.